pt

SUNY

PHYSICS OF TECHNOLOGY

COORDINATED BY AMERICAN INSTITUTE OF PHYSICS

CATHODE RAY TUBE

Electric Fields and Forces

The Physics of Technology modules were coordinated, edited, and printed copy produced by the staff at Indiana State University at Terre Haute, Indiana. The staff involved in the project included:

Philip DiLavore .... Editor
Julius Sigler .... Rewrite Editor
Mary Lu McFall .... Copy and Layout Editor
B. W. Barricklow .... Illustrator
Stacy Garrett .... Compositor
Elsie Green .... Compositor
Lauren Eli .... Compositor
Donald Emmons .... Technical Proofreader

In the early days of the Tech Physics Project A. A. Strassenburg, then Director of the AIP Office of Education, coordinated the module quality-control and advisory functions of the National Steering Committee. In 1972 Philip DiLavore became Project Coordinator and also assumed the responsibilities of editing and producing the final page copy for the modules.

The National Steering Committee appointed by the American Institute of Physics has played an important role in the development and review of these modules. Members of this committee are:

J. David Gavenda, Chairman, University of Texas, Austin
D. Murray Alexander, DeAnza College
Lewis Fibel, Virginia Polytechnic Institute & State University
Kenneth Ford, University of Massachusetts, Boston
James Heinselman, Los Angeles City College
Alan Holden, Bell Telephone Labs
George Kesler, Engineering Consultant
Theodore Pohrte, Dallas County Community College District
Charles Shoup, Cabot Corporation
Louis Wertman, New York City Community College

This module was written and tested at the State University of New York at Binghamton.

The authors wish to express their appreciation for the help of many people in bringing this module to final form. The criticisms of various reviewers and the cooperation of field-test teachers have been most helpful. Several members of the staff of the State University of New York at Binghamton also deserve special recognition for their contributions. They are: Lisa Briguglio, Felix K. Chen, Duane A. Damiano, Eugene C. Deci, Barry R. DeGraff, Max Eibert, Steve I. Finette, Chung-Yu Fu, Leonard R. Kelly, Stevan H. Leiden, Laurie A. Sperling, William Standish, and Howard M. Zendle.

Cathode Ray Tube

ISBN 0-07-001721-2

1 2 3 4 5 6 7 8 9 0 E B E B 7 8 3 2 1 0 9 8 7 6 5

CATHODE RAY TUBE

A Module on Electric Fields and Forces

SUNY

Carl R. Stannard and Bruce B. Marsh, Project Co-Directors

Arnold Benton, American Institute of Physics

Ludwig P. Lange, Broome Community College

MCGRAW-HILL BOOK COMPANY

NEW YORK
ST. LOUIS
DALLAS
SAN FRANCISCO
MONTREAL
TORONTO

TABLE OF CONTENTS

You are using a cathode ray tube whenever you watch television. The picture is formed by 525 horizontal scans of the electron beam. Each scan takes about 0.000063 seconds (63 microseconds). The signal from the TV camera causes the intensity of the beam in the viewer's CRT to change as it scans, producing the light and dark patterns that make up the picture on the tube's phosphor coat.

Photograph courtesy of the Office of Educational Communications, State University of New York at Binghamton.

CATHODE RAY TUBE

MATHEMATICS PREREQUISITES

1. Trigonometry—ability to use sin, cos, tan
2. Addition of vectors
3. Ability to use exponential notation

LAWS AND PRINCIPLES TO BE EXTRACTED

1. Conservation of charge
2. Coulomb's Law
3. Concept of a field
4. Force on a charged particle in an electric field
5. Application of Newton's Second Law to charged particles moving in uniform electric fields

MATH PREREQUISITES CHECK

There are some things you should know and be able to do before you begin this module. Try to answer the following questions. If you can handle them all easily, you should be able to read the module and do the experiments without difficulty. If you have trouble with any of these questions, ask your instructor for help on those items before you begin to study the module.

A. Mathematical Skills

1. For the right triangle in Figure 1:
   a. $\sin\theta =$
   b. $\cos\theta =$
   c. $\tan\theta =$

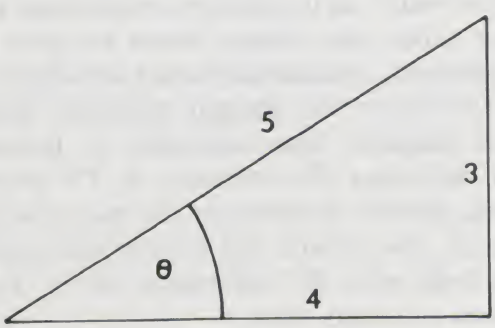


Figure 1.

2. A man walks four miles east, then he walks four miles in a direction which is north of west. Where is he in relation to his starting point?
3. Write as a number between one and ten multiplied by the proper power of ten:
   a. 12,400
   b. 0.00309
4. Carry out the indicated calculations:

$$\frac{3 \times 10^{10} \times 6 \times 10^{-27}}{9 \times 10^{-19}}$$

B. Vocabulary

1. The following words are used in connection with forces on an object and the motion that may result. Can you define them?
   a. force
   b. attract
   c. repel
   d. deflect
   e. mass
   f. velocity
   g. acceleration
   h average
   i. constant
   j. uniform
2. The following words are used in connection with work done by a force and the changes in energy which may result. Can you define them?
   a. work
   b. energy
   c. kinetic energy
   d. potential energy
   e. conservation
   f. joule
   g. microjoule
3. The following words are used in connection with vectors. Can you define them?

a. vector
b. component
c. magnitude
d. tangent
e. parallel
f. perpendicular

4. The following terms are used in connection with electrical apparatus. Can you define them?
   a. electricity
   b. terminal
   c. electrode
   d. cathode
   e. battery
   f. oscilloscope
   g. deflecting plates
   h. banana plug
   i. AC
   j. DC

GOALS FOR THIS MODULE

The list of learning goals below should help your study of the experiments, reading material, and problems included in this module. If you are able to perform all of the tasks in this list, you should have no trouble with the test that will follow at the end of the module. When you have finished this module, you should be able to:

1. Give the rules for attraction and repulsion of electric charges.
2. Describe the transfer of electric charge from one body to another and the effect of electric charge on metal surfaces.
3. Define electric field, electric intensity, potential difference or voltage.
4. State the names of the Standard International (SI) units for all quantities that appear in the equations of this module.
5. Use the law $F = (KQ_1Q_2)/r^2$ and the expression $F = qE$ to solve problems.
6. Discuss the properties of field lines and equipotential surfaces and tell why they intersect at right angles.
7. Determine the path of a charged particle that enters an electric field perpendicular to the field.
8. Calculate the final kinetic energy and velocity of a charged particle, given the initial velocity and the potential difference through which it moves.
9. Using the apparatus of Experiment 3, measure the deflection of an electron beam on the face of a CRT as a function of the voltage on the deflecting plates.

WHAT YOU WILL STUDY

The main topic of this module is electricity. Electricity is so common in our lives that no one needs to be told how important it is. Knowing the basic ideas of electricity is a first step toward understanding how electrical things work. The main ideas you will learn here are:

1. That there are two kinds of electric charge (called positive and negative)
2. That two or more charges always exert forces on each other (you will learn how to calculate the size and direction of these forces)
3. The meaning of the term *electric field*
4. How to find the forces acting on a charged particle in an electric field
5. The meaning of electrical potential energy
6. The definition of kinetic energy
7. The importance of conservation of energy

The electrical device you will study is the cathode ray tube (CRT). It is the main component of TV sets, automobile engine analyzers, patient care units in hospitals, and oscilloscopes. The CRT and a few other devices (such as the electron microscope and x-ray tubes) use electric forces to speed up (accelerate), concentrate (focus), and deflect a stream (beam) of charged particles. Sometimes magnetic forces are used for focusing and deflecting (for instance, in TV picture tubes, particle accelerators and mass spectrographs). The physics you learn in this module will help you to understand all of these devices and many more.

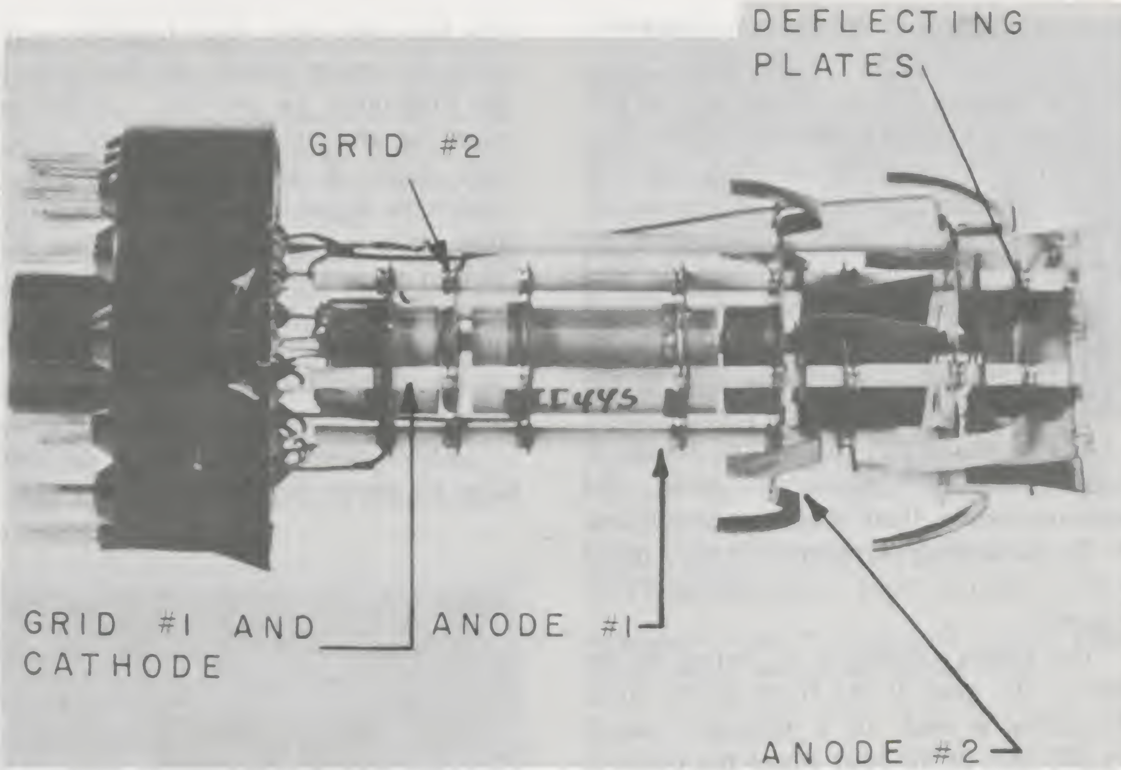


Figure 2A. A photograph of the working parts of a cathode ray tube.

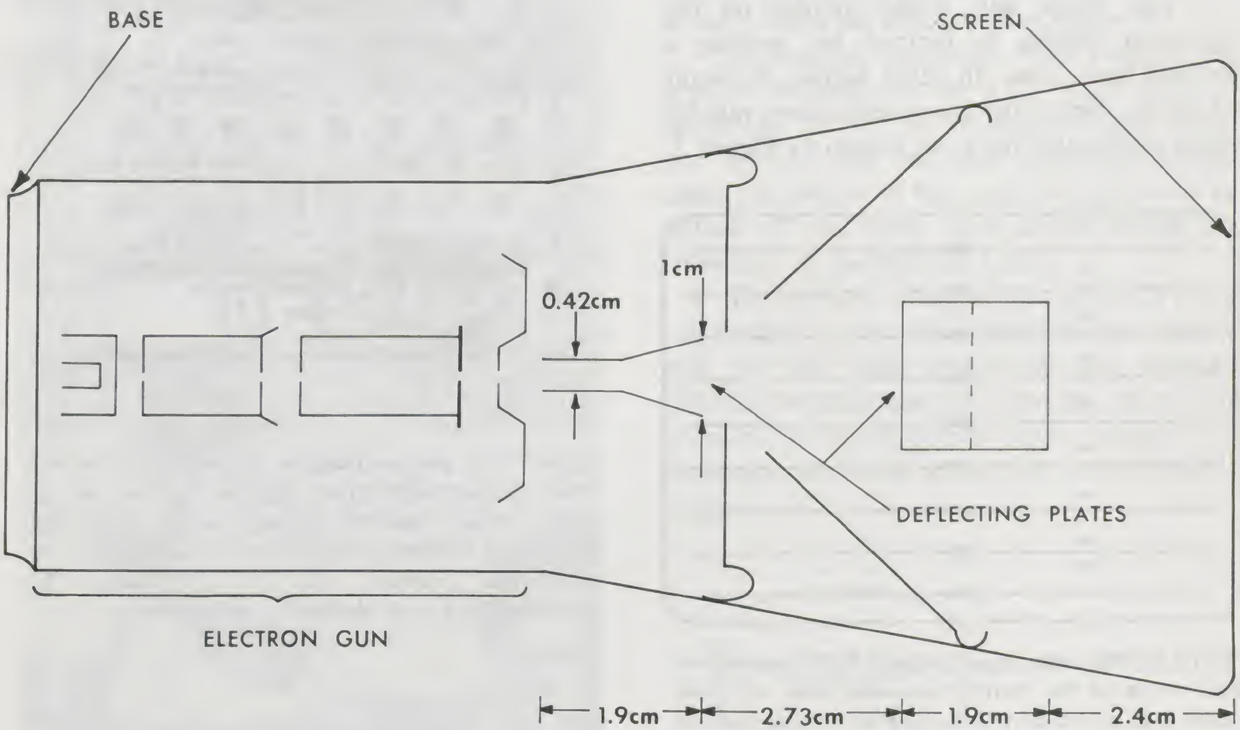


Figure 2B. A drawing of the same CRT, showing dimensions.

THE CATHODE RAY TUBE

The parts of a cathode ray tube (CRT) are shown in Figures 2A and 2B. They are a glass container, called an *envelope;* an *electron gun,* which produces the electrons; *deflecting plates;* a *screen,* which gives off light where electrons strike it; and the base through which the electrical connections are made.

The envelope holds and protects the other parts and keeps them in a vacuum.

The electron gun does three things: it supplies electrons,* accelerates them, and shapes or focuses them into a narrow beam.

The deflecting plates control the path of the beam and can make it strike anywhere on the screen.

The screen consists of a coating on the inside of the glass at the front of the tube. The coating is made of a *phosphor,* which gives off light at the spot where the electron beam strikes.

All electrical connections are made through the base.

The black and white picture on the television screen is formed by making a focused beam *scan.* In other words, the point where the beam hits the screen moves rapidly along horizontal lines, as shown in Figure 3.

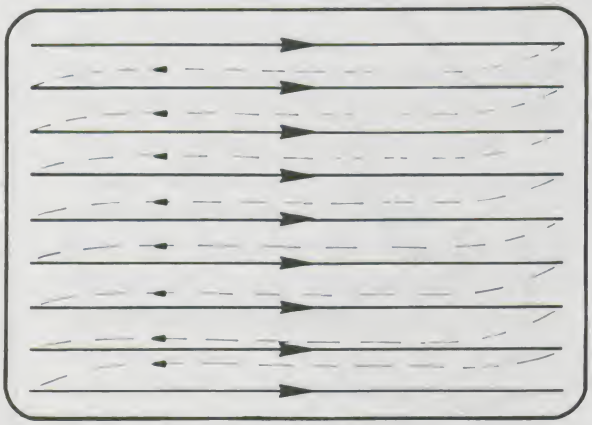


Figure 3. The beam in a television tube scans across lines which fill the entire screen. The lines are much closer than shown here, and there are several hundred of them.

*An electron is a small charged particle. Its radius is less than 10^{-14} meters (m); its mass is 9.11×10^{-31} kilograms (kg); and it has a negative charge of 1.60×10^{-19} coulombs (C).

The lines are very close together, and they cover the entire screen. As the beam scans, the brightness, or *intensity,* of the spot is varied to give each point on the screen the right shade of white, black, or gray. The brightness depends on the number of electrons striking the screen per second. For the light to be seen by the eye, many electrons must strike near the same point. The control knob marked *brightness* on a TV set (*intensity* on an oscilloscope) allows you to control the number of electrons in the beam.

Other applications of the cathode ray tubes are shown in Figures 4, 5, 6, and 7.

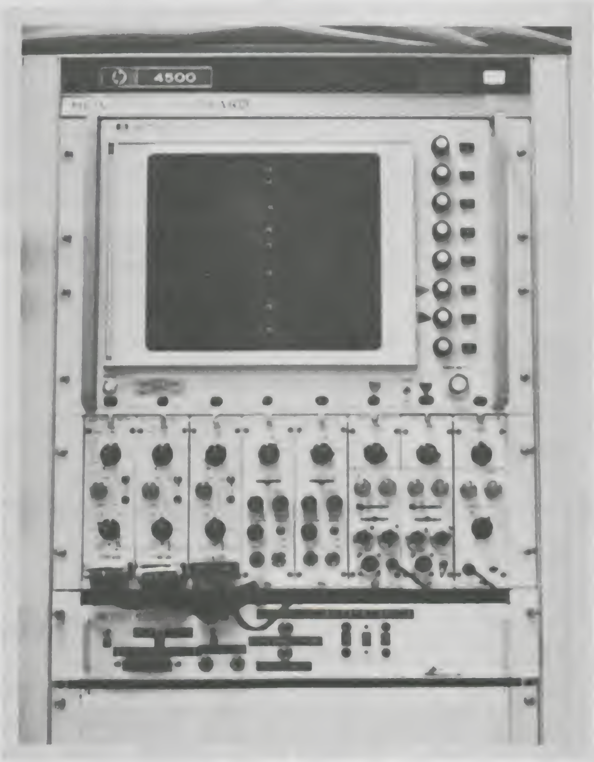


Figure 4. A general purpose physiological monitor which displays eight traces on the large cathode ray tube. Three channels display electrocardiograph traces, two channels display heart sounds, two are for intercardiac pressure, and one is a channel for recording the rate of change of blood pressure.

The free electrons for a cathode ray tube are supplied by a process called *thermionic emission.* In *thermionic emission* electrons are boiled off with heat from a piece of metal which is called the *cathode.* This effect was first observed by Edison in 1883.

Much research has gone into developing cathodes which last a long time and which can be used to operate devices like vacuum tubes, cathode ray tubes, and x-ray tubes. The problem is that many metals don't last very long at the high operating temperatures needed to get enough electrons emitted; the metal tends to boil off along with the electrons. The most common solution to this problem is the use of a metal wire coated with a certain oxide. This has the effect of lowering the operating temperature needed to produce enough electrons by thermionic emission. This type of cathode is called an *oxide-coated cathode.*

Figure 5. Nurses can watch the electrical pulses produced by cardiac patients' hearts on the cathode ray tube monitors located in a central display panel.

Photograph 4 and 5 courtesy of Wilson Memorial Hospital, John City, New York.

Figure 6. The signals from the radar scanner are displayed on this cathode ray tube in the Broome County (N.Y.) Airport control tower.

Figure 7. This picture of an older radar display tube, formerly used in the radar room of the Broome County Airport, shows the cathode ray tube and some of the electronics associated with a radar display system.

Photograph 6 and 7 courtesy of Federal Aviation administration and Broome County Airport.

Modern oxide-coated cathodes often are cylindrical caps which surround a heating wire, called the *filament.* The filament is heated by passing a current through it and it, in turn, heats the cathode. See Figure 8.

In normal operation, high voltages are applied to parts of the CRT. Care must be taken not to turn on the high voltages before the cathode has reached operating temperature, or pieces of the oxide coating may be pulled off the core. This would reduce the emission and damage the tube.

The motion of electrons in the CRT and the electric forces which produce that motion will be the main topics of this module. Electric forces come from and act on electric charges. To understand these forces it is necessary to know something about electric charge.

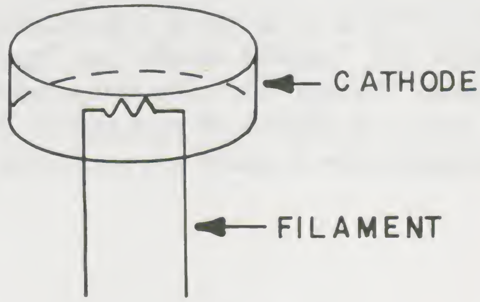


Figure 8.

ELECTRIC CHARGE

Have you ever walked across a rug and gotten a shock when you touched another person? Have you ever run a comb through your hair and noticed that the comb will pick up small pieces of paper? Have you ever noticed nylon clothing cling and sometimes crackle as you take it off? If your answer to any of these questions is yes, you have observed electric charges in action.

Electric charges are a part of all ordinary matter. There are two kinds of charge—positive and negative. The things we use, see, and touch in our daily lives have equal numbers of positive and negative charges in them. They are said to be *neutral* or uncharged. Sometimes, when things are rubbed together, a separation of charge takes place. For example, when a plastic rod is rubbed with a wool cloth, the plastic rod ends up with more negative charge and the wool cloth with more positive charge than they had before. They are now said to be "charged," one negatively and the other positively. Charges within neutral objects can also be separated under some conditions. Thus it is possible for negative charges in an object to move to one end of the object leaving a shortage of negative charges on the other end. This is the same as saying one end has a negative charge and the other end has a positive charge. Charge is never created or destroyed. Charges can be moved around, separated, or recombined, but the net charge—that is, the total amount of positive charge minus the total amount of negative charge—never changes. This is the principle of *conservation of charge.*

EXPERIMENT 1. Electric Charge

In this experiment you will study the effects of electric charge, first on a piece of metal, then on the electron beam in a cathode ray tube.

Let's start examining the behavior of charged objects. Cut a triangular piece of aluminum foil about one-half inch on each side. Form a small loop at one end of a nylon thread. Crimp one corner of the triangle around this loop and attach the other end of the thread to a support, allowing the aluminum to swing freely. Handle the string as little as possible or moisture from your hands may spoil the results. If you want to remove charge from the aluminum, simply touch it with your finger. This has the effect of grounding the aluminum.

Procedure

Follow the sequence of experiments described, keeping a written record of what you do and what you see.

1. Rub the hard-rubber rod with a piece of Saran Wrap and hold the rod near the suspended aluminum foil without touching them together.

2. Hold the piece of Saran Wrap near the foil without letting them touch.

3. Touch the foil with the rod.

4. Remove the rod and hold the Saran Wrap near the foil.

5. Touch the foil with the rod, then touch the foil with your finger. Now approach the foil with the rod.

6. Try similar experiments using other charged materials (glass rod rubbed with silk cloth; rubber rod rubbed with cat's fur).

Questions

1. Why should you ground (by touching) the aluminum before each new observation?

2. Which of the things that you tried show that like charges repel and unlike attract? Explain how each shows it.

3. What difference, if any, did you see in the behavior of the foil when held near a charged rod before and after being touched with the rod? Explain in terms of charge.

4. What effect does touching the foil with your hand have? Explain, using the idea of charge.

5. What happens to the charge on the foil if the string is moist?

6. Will charge stay on the foil forever if the foil is not touched?

7. What is the Principle of Conservation of Charge? What did you see that agrees or disagrees with this principle?

Now, find out whether electrically charged rods have any effect on the electron beam of a cathode ray tube. To do this, you may use an oscilloscope if one is available, or you may use the cathode ray tube (CRT) that is provided with this module. The cathode ray tube is shown in Figure 9, and a schematic diagram of it is shown in Figure 10. In this circuit, the metal box, or *chassis*, is grounded and used as part of the circuit. Anything connected to it is said to be at the "common voltage" or "chassis voltage." The common voltage is also called the "ground," because it is at or very near the voltage of a water pipe or something else which is well connected to

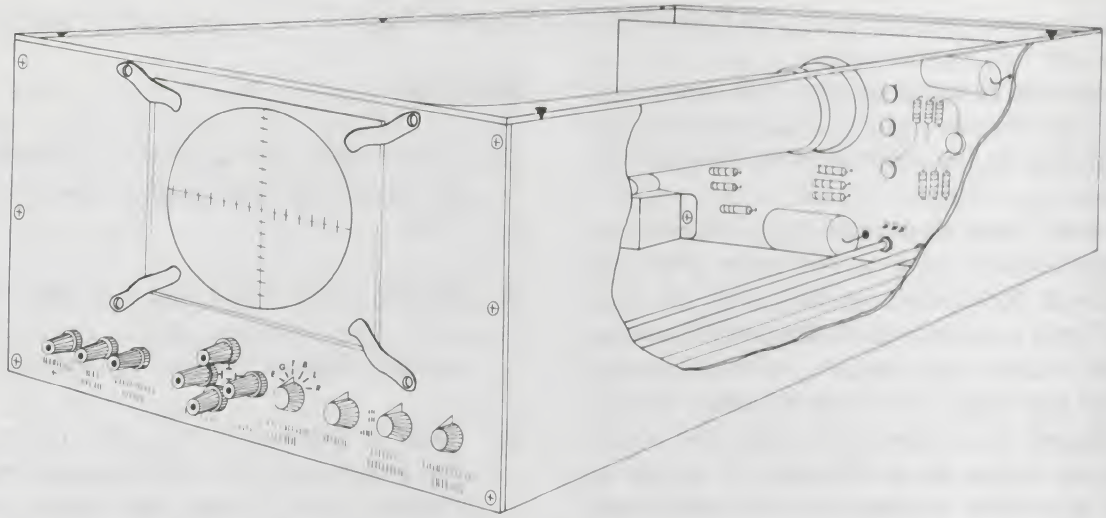


Figure 9.

the earth. Usually, most of the voltages in a circuit are positive with respect to the common. In this case, though, the circuit voltages are negative with respect to the common, for safety reasons.

If you use an oscilloscope, let your instructor advise you how to operate it. If you use the CRT which was designed for this module, connect the meter provided for voltage measurements so that the positive terminal of the meter goes to the binding post called *common*, and the negative terminal goes to the post called *Acceleration Voltage Meter.*

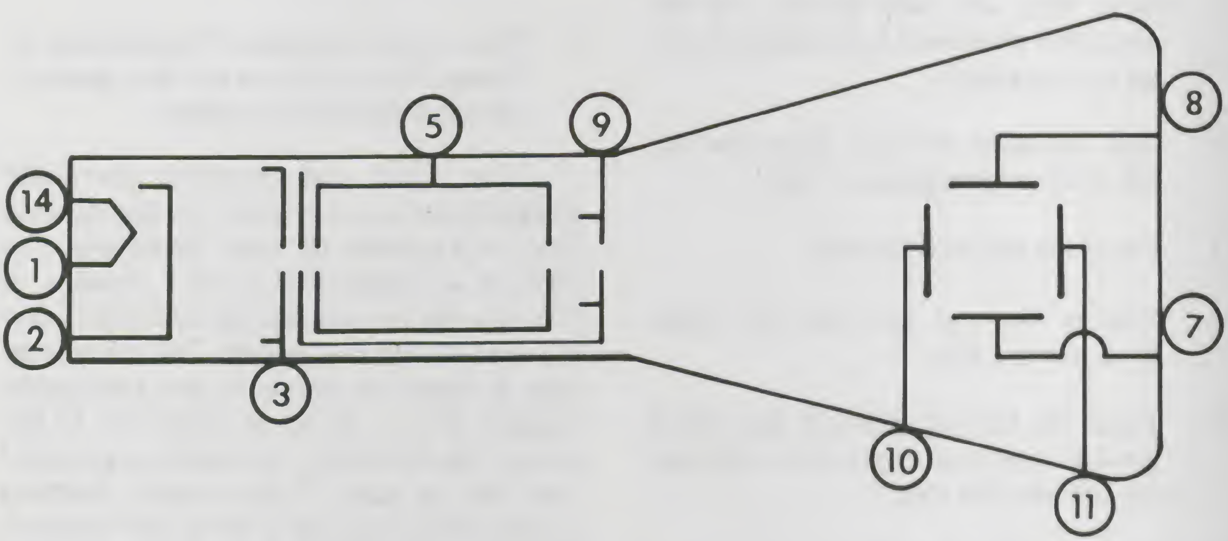


Figure 10. Schematic of the CRT. The numbered circles represent connections to the pins in the socket into which the CRT is plugged. They are as follows:

1 and 14–Heater
2–Cathode
3–First Grid
5–First Anode
9–Second Grid and Second Anode
7, 8, 10, and 11–Deflection Plates. (These are drawn as if you were looking at them through the front of the tube.) When the Deflection Plate Selector Switch is on the "External" position, these plates are connected to the L, R, T, and B connectors on the front.

The AC power switch and the Acceleration Voltage control use the same knob. Turn the AC power on, but do not turn the high voltage up very far.

Soon you should be able to see the red glow of the filament behind the cathode. Turn the deflection plate selector switch to any position *other than* external. Increase acceleration voltage until the meter indicates about 500 V. Adjust the *Focus*, which controls the voltage of anode #1, so that the electron beam spot on the tube face is as small as possible.

Now you are ready to continue.

a. Remove the plastic panel which is located in front of the CRT. (Be very careful not to hit the CRT. There is a high vacuum inside the tube, and you could be hurt by flying glass if it should break while the protective plastic cover is off.) Move a charged rod near the face of the CRT and observe the effect. When you have completed this part, replace the plastic panel over the front of the CRT.

b. Turn the deflection plate selector switch to *external.* This will connect each of the four deflection plates in the CRT to one of the four *Deflection Inputs* on the panel.

   Is there any effect on the electron beam when you move a charged rod near one of the deflection plate terminals? You may find it helpful to plug a lead wire into the terminal and to bring the rod near the free end of the lead.

   The spot may disappear because of stray charges and fields inside the tube. If this occurs, turn the deflection plate selector switch away from the *external* position to some other position until the beam reappears, then turn it back to *external.*

c. Does it make any difference whether the charged rod is moved toward or away from a given deflection plate terminal? Note the direction in each case. Is the deflection permanent or pulse-like?

d. Connect a battery or low-voltage DC power supply (from about 6 to 25 V or so) across one pair of deflection plates. Now observe the beam deflection. Is the deflection permanent?

e. Is it possible to determine whether the charge on the rod is positive or negative by comparing the directions of the deflections which you observe for the rod and the battery? Plan your own experiment and see if it works.

f. (Optional.) If you have a low frequency AC signal generator (oscillator) available, set it at its lowest frequency and connect it to one pair of the deflection plates. Why does the beam move back and forth?

Questions

1. When a charged rod is moved rapidly toward a deflection plate terminal of the CRT and then pulled back, the electron beam is seen to deflect in opposite directions. Can you explain why?

2. It is known that if rubber is rubbed with cat's fur, the rubber becomes negatively charged and the fur becomes positively charged. In the case of glass rubbed with silk, the glass takes on positive charge and the silk negative charge. Do your experimental results agree with these facts?

COULOMB'S LAW

In 1784 a French physicist named Charles Coulomb measured the force between two small charged spheres. He found that the force depends on: (1) the amount of charge on each sphere and (2) the distance between them. Keeping the distance between the charges the same, Coulomb found that if the amount of either one of the charges is doubled, the force is doubled; if tripled, the force is tripled, and so on.

Coulomb also found that when the charges are kept the same, doubling the distance between the charges made the force one-quarter of what it formerly was. When the distance was made M times as large, the force became $1/M^2$ of what it formerly was. The way the force changes with the charge strength and distance is called *Coulomb's Law.* If F is the force, Q_1 and Q_2 the amounts of the two charges, and r the distance between them, Coulomb's Law can be written as a formula:

$$F = \frac{KQ_1Q_2}{r^2} \qquad (1)$$

The quantity K is a constant that depends on the units that are used. In the SI (Standard International) system of units $K = 9.0 \times 10^9 \,\mathrm{N{\cdot}m^2/C^2}$, for charges which are in the air or in a vacuum. In this system of units the unit of force is newtons (N), the unit of charge is coulombs (C), and the unit of distance is meters (m).

Point Charges

The forces acting on real charged bodies can get rather complicated, so physicists have invented a fictional charged body, called a *point charge.* A point charge is at a geometrical point, which occupies no space, and this greatly simplifies the solution of problems. The force between two point charges acts along the line joining them. For unlike charges (+ and −), the force is attractive (Figure 11) as you have discovered for yourself.

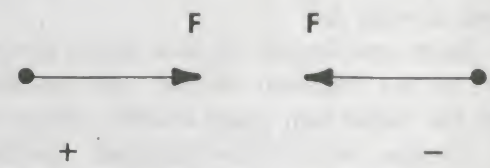


Figure 11. Unlike charges attract.

For like charges (+ and +) or (- and -), the force is repulsive (Figure 12).

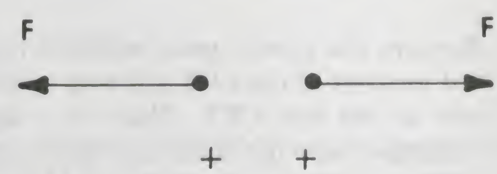


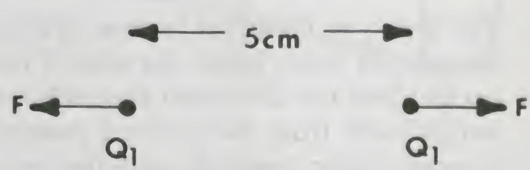
Figure 12. Like charges repel.

Example. Two charges are 5.0 cm apart. (All of our problems will be done in the air, where $K = 9 \times 10^9 \,\mathrm{N{\cdot}m^2/C^2}$.) The charges are 25 and 15 μC. What is the force between them? Is it attractive or repulsive? Note: One coulomb is a huge amount of charge. It is more convenient to use the smaller unit:

$$1 \text{ microcoulomb} = 10^{-6}\,\mathrm{C}$$

The following steps show a good method for solving any problem:

1. Draw a diagram.



2. Write the equation to be used.

$$F = \frac{KQ_1Q_2}{r^2}$$

3. List all known and given values, converting to SI units where necessary.

$$K = 9 \times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2$$

$$Q_1 = 25\ \mu\text{C} = 25 \times 10^{-6}\ \text{C}$$

$$Q_2 = 15\ \mu\text{C} = 15 \times 10^{-6}\ \text{C}$$

$$r = 5\ \text{cm} = 0.05\ \text{m}$$

4. Put the numbers into the formula.

$$F = \frac{(9\times 10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)(25\times 10^{-6}\ \text{C})(15\times 10^{-6}\ \text{C})}{(0.05\ \text{m})^2}$$

5. State the result.

$$F = 1.35 \times 10^3\ \text{N}$$

(This is a repulsive force of about 230 pounds. We know it is repulsive because the answer is a positive number.)

PROBLEMS AND QUESTIONS

1. Two point charges are a distance d apart. What happens to the electric force between them if:

   a. the charge on one of them is doubled?
   b. the charge on each is doubled?
   c. the charge on each is tripled?

2. Calculate the force exerted on a 40°C positive charge by a negative 50°C charge which is 50 cm away.

3. Calculate the electric force between a proton (charge $+1.6 \times 10^{-19}$ C) and an electron (charge -1.6×10^{-19} C) which are 10^{-10} m apart. (This is approximately their separation in a hydrogen atom.)

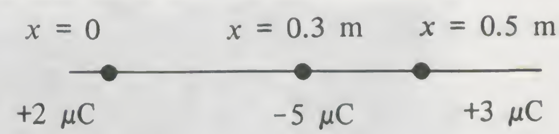
4. Two point charges repel each other with a force of 1.6×10^{-19} N when they are 1.0 m apart. Which of the following is certainly true? The charges are:

   a. both negative
   b. both positive
   c. unlike
   d. like

5. If the distance between the two charges in question 4 is increased to 4.0 m, does the force between the charges become

   a. 1.0×10^{-5} N?
   b. 6.4×10^{-4} N?
   c. 4.0×10^{-5} N?
   d. 8.0×10^{-5} N?

6. Three charges are placed along a straight line as shown:



   a. What is the magnitude and direction of the force on the +2 μC charge?
   b. What is the magnitude and direction of the force on the negative charge?

(Hint: To do this problem, you must know the experimental fact that the force one charge exerts on a second charge is not changed by the presence of a third charge. However, the third charge also exerts a force on the second charge.)

7. Three charges are placed on a plane in the following way:

   a. A 2 μC positive charge is placed at $x = 0, y = 0$.
   b. A 5 μC negative charge is placed at $x = 3$ m, $y = 0$.
   c. A 3 μC positive charge is placed at $x = 0$, $y = 2$ m.

1. What is the magnitude of the force on the 2 μC charge?

2. What is the direction of the force (up and right, up and left, down and left, or down and right)?

(Hint: Remember that forces are vectors.)

ELECTRIC FIELDS

Electric fields are used to accelerate, focus, and deflect the electron beam of cathode ray tube. Magnetic fields are used for beam deflection in TV picture tubes and to steer charged particles in particle accelerators. Fields are important in all devices that use charged particles.

Electric fields exist because of charged particles. Each electric charge is surrounded by an electric field. To know if there is an electric field at some point, we must place a small charge as a test charge at that point. If the test charge is acted on by an electric force, then an electric field exists at that point. This defines the electric field.

As an example, let us find the electric field which is present at a point P because of the presence of a charge $+Q$ at the point O (see Figure 14), where the distance OP is r. To determine the electric field at P, we must put a positive test charge there and measure the force on it. Then we divide the force by the size of the charge. Let q be the size of the test charge put at point P.

For this simple case, we can use Coulomb's Law (Equation 1) to calculate the

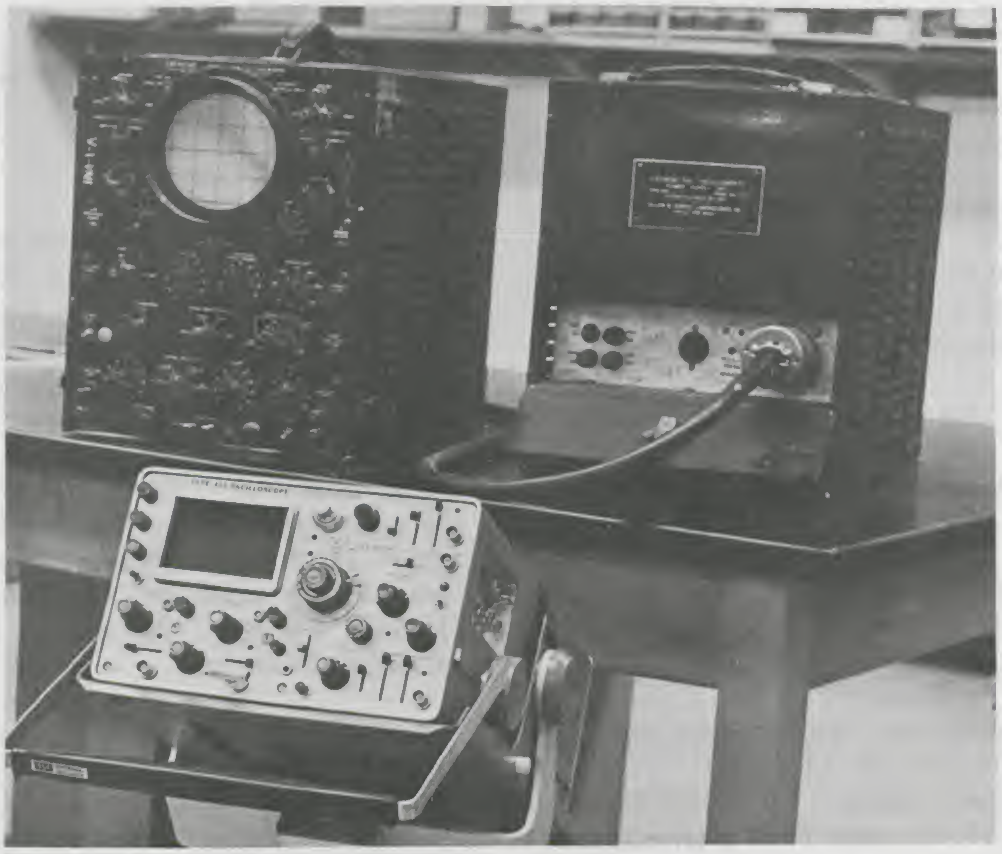


Figure 13. The cathode ray oscilloscope was the first device to utilize the cathode ray tube. The large oscilloscope shown, which has a power supply as large as itself, was built in the 1940's. The modern oscilloscope is not only more compact, but it can do more, better.

Photograph courtesy of the Nuclear Physics Laboratory, State University of New York at Binghamton.

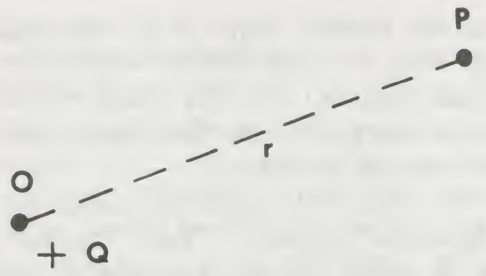


Figure 14. Diagram to obtain field of point charge.

force acting on the test charge. (Of course, we could not do this unless Coulomb and others had taken the time to do the experiments needed to discover and verify his law.) That force is:

$$F = (KQq)/r^2 \qquad (2)$$

If we now divide the force, F, by the charge, q, which we put at P, we get the force per unit charge:

$$F/q = KQ/r^2 \text{ (For a point charge)} \qquad (3)$$

The letter E is commonly used for F/q, and it is called the *electric field strength.* (Physicists also use the term *electric intensity*.)

$$E = F/q \qquad (4)$$

E is a force divided by a charge, which in SI units is newtons/coulomb (N/C). The direction of the electric intensity is taken to be the same as the direction of the force, F, on a positive test charge. The electric intensity, E, is a vector; it has both magnitude and direction.

Example. What is the electric intensity at a distance of 1 cm from an electron which has a charge $e = 1.6 \times 10^{-19}$ C?

1. Draw a diagram.

   A positive charge placed at P would be attracted to the negatively charged electron. The force F is drawn in the direction from P to O to show that attraction.

2. Write the equation to be used. The electric intensity for a point charge is given by combining Equations (3) and (4):

$$E = KQ/r^2$$

3. List all known and given values, converting to SI units where necessary.

$$K = 9.0 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$$
$$Q = e = -1.6 \times 10^{-19} \text{ C}$$
$$r = 1 \text{ cm} \times 1 \text{ m}/100 \text{ cm} = 0.01 \text{ m}$$

4. Enter the numbers in the equation as positive.

$$E = [(9.0 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2)/(0.01 \text{ m})^2]\,(1.6 \times 10^{-19} \text{ C})$$

5. State the result.

$$E = 1.44 \times 10^{-5} \text{ N/C (Toward the electron)}$$

PROBLEMS AND QUESTIONS

1. What is meant by electric intensity? electric field strength?

2. How would you determine the direction of an electric field?

3. A positive test charge of 200°C has a force of 0.50 N acting on it at a certain point in an electric field.

   a. Calculate the electric intensity at this point.
   b. What would the force be on a test charge twice as great if it were placed at this point?

4. The electric intensity at a certain point is 11,000 N/C. Calculate the magnitude of the force on a 3 μC charge placed at that point.

5. One model of the hydrogen atom proposes that the nucleus is a stationary, positive charge of magnitude 1.6×10^{-19}C and the electron travels around the nucleus in a circle of radius 5×10^{-11}m. What is the electric intensity at the location of the electron?

6. A 2 μC positive charge and a 3 μC negative charge are 4 cm apart. What is the magnitude and direction of the electric intensity at a point halfway between them?

MORE ABOUT ELECTRIC FIELDS

Fields due to electric charges at rest are called *electrostatic fields.* They are pictured as *field lines* starting on positive charges and ending on negative charges. A field line is an imaginary line along which a tiny, massless test charge would travel if it were released in the field. For example, as shown in Figure 15, if the positive test charge were placed in the field produced by a large positive charge, it

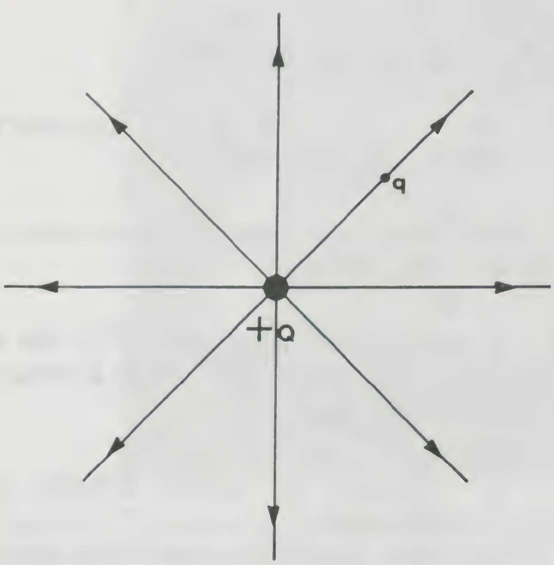


Figure 15. Wherever the test charge, q, is placed, it is repelled directly away from the point charge, $+Q$.

would be pushed away by the electrostatic force. Thus, the field lines are drawn directly outward (*radially*) from the charge $+Q$. For a negative charge, $-Q$, the field lines would be drawn radially inward.

To map field lines we make use of *equipotential surfaces.* "Equi" means the same or equal. *Electric potential* is electric potential energy per unit charge. To explain equipotential surfaces let's consider first the gravitational case, which is very similar.

When a heavy object is lifted and then released, the earth pulls on the object, the object accelerates as it falls, and thus it acquires *kinetic energy.* (Kinetic energy is the energy an object has because it is moving. It is equal to one-half the mass times the square of the velocity of the object, $\frac{1}{2} mv^2$.) Before the object was released, it had the ability to acquire this kinetic energy. This ability is called *gravitational potential energy,* and it depends on the gravitational pull and the height, or level, to which the object was raised. A certain object at some level will have a particular gravitational potential energy. An object with twice the mass, at the same level, will have twice the energy, and so on. Then, for some particular level, if the gravitational potential energy of an object is divided by the mass of the object, the same number results, no matter what object is used. This number is energy per unit mass, and it is called *gravitational potential.* It is a property of the level chosen. All points on a given level have the same gravitational potential. The levels are really layered surfaces parallel to the surface of the earth and are called *gravitational equipotential surfaces.* On geographical maps they appear as contour lines.

In the electrical case, if you hold a negative charge near a stationary positive charge and release it, the negative charge will accelerate toward the positive charge, thus acquiring kinetic energy. We say that the separated charges possess potential energy, and because this energy clearly results from electric forces, we call it *electric potential energy.* It too depends upon position. For a one-unit electric test charge in an electric field, there are levels or surfaces on which the

electric potential energy remains the same. The electric potential energy per unit charge is called *electric potential.* A surface which has the same electric potential everywhere on it is called an *electric equipotential surface.*

Electric potential is measured in *volts.* Between two different equipotential surfaces there exists a *potential difference,* which is also called a *voltage*; this too is measured in volts.

Since all points on an equipotential surface are at the same potential, a charged particle can be moved from one point to another on an equipotential surface without changing its potential energy. Changes of electric potential energy, and thus of potential, result from work done by or against an electric force. But no work is done by the field on a charged particle as it moves along an equipotential. How is this possible, since work is the product of the force by the distance moved? Actually, work equals force times distance only when at least part of the force acts in the direction of the distance moved. This is explained in Figure 16A, B, and C.

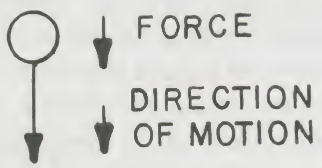


Figure 16A. When a ball is dropped, the gravitational force (weight) acts in the direction of the motion, and work is done on the ball.

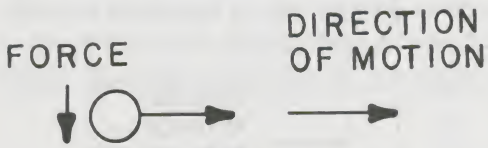


Figure 16B. When the ball is rolled along a smooth floor, except for friction, the only force is its weight, acting downward. If it weren't slowed down by friction, the ball would roll until it hit something.

If the direction of the force and the path of the motion are at right angles, no work is done by the force. Motion along an equipotential surface must, therefore, be perpendicular to the force of the field. So equipotential surfaces are everywhere perpendicular to the field lines.

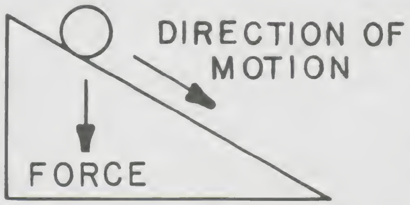


Figure 16C. When the ball rolls down the tilted smooth surface, part of the force acts in the direction of motion. Work is done, but not as much as when the ball falls the same distance as it moves along the surface.

Field lines are drawn in the direction of the field. If the field line is curved, the direction of the field at any point is the direction of the tangent drawn to the field line at that point (see Figure 17). Because field lines are in the direction of the force, it follows that field lines and equipotential surfaces always cross at right angles.

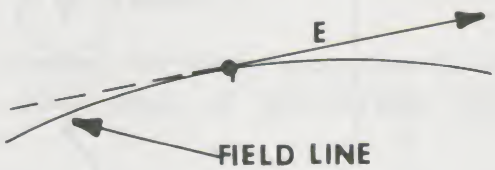


Figure 17. Tangent to a field line.

EXPERIMENT 2. Mapping Electric Fields

In this experiment you will do the following:

1. Map the electrostatic field between two parallel plates, including the fringe field.
2. Map the electrostatic field for a set of flared CRT deflecting plates.
3. Map the accelerating field of a CRT.
4. Map the field inside a closed, charged metallic conductor.

Procedure

1. Wire the equipment as shown in Figures 18 and 19. While some of the students are doing this, others in the group should be preparing the materials in the next step.

2. Paint the forms shown in Figures 20, 21, 22, and 23 on the special field-mapping paper provided for this purpose, using silver conducting paint.

3. Mount one of the sheets of field-mapping paper prepared in step 2 on the board provided.

4. With the negative terminal of the voltmeter connected to the negative terminal of the battery (or voltage source) and the positive terminal connected to the voltage divider, set the voltage divider so that the voltmeter reads 5 V (or to about ¼ of the battery voltage, if you don't have a 20-V battery).

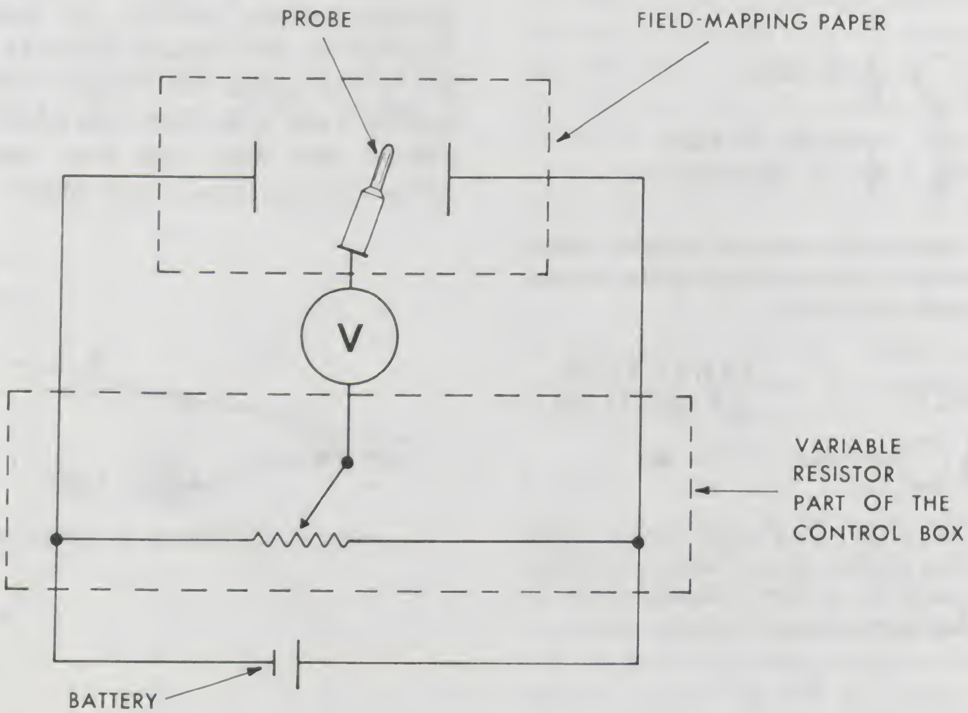


Figure 18.

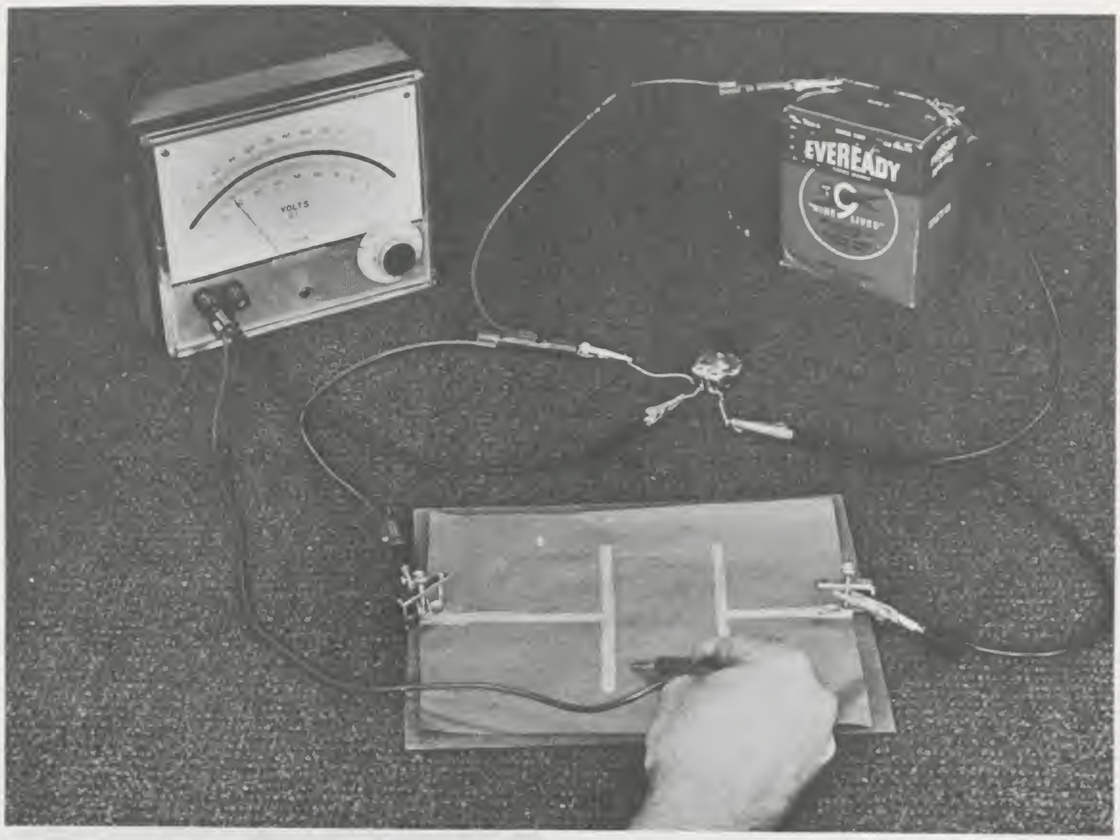


Figure 19.

5. Disconnect the voltmeter lead that is connected to the negative battery terminal. Touch this lead to the field-mapping paper. Locate the points which produce no movement of the meter needle (zero voltage). Mark these points, which are all at a potential of 5 V. (That is, those points on the paper are at the same potential as the side of the voltmeter which is attached to the voltage divider. In step 4 we set this so that it was 5 V higher than the potential of the negative side of the battery, which we call zero.) Be sure to take enough points so that you can draw the path of this equipotential line between the plates and also beyond the plates. Mark the voltage of this line on the field-mapping paper.

6. Repeat steps 4 and 5 for 10 V, 12 V, 15 V, 17 V, and 20 V.

7. Repeat the entire procedure for the other sheets of field-mapping paper.

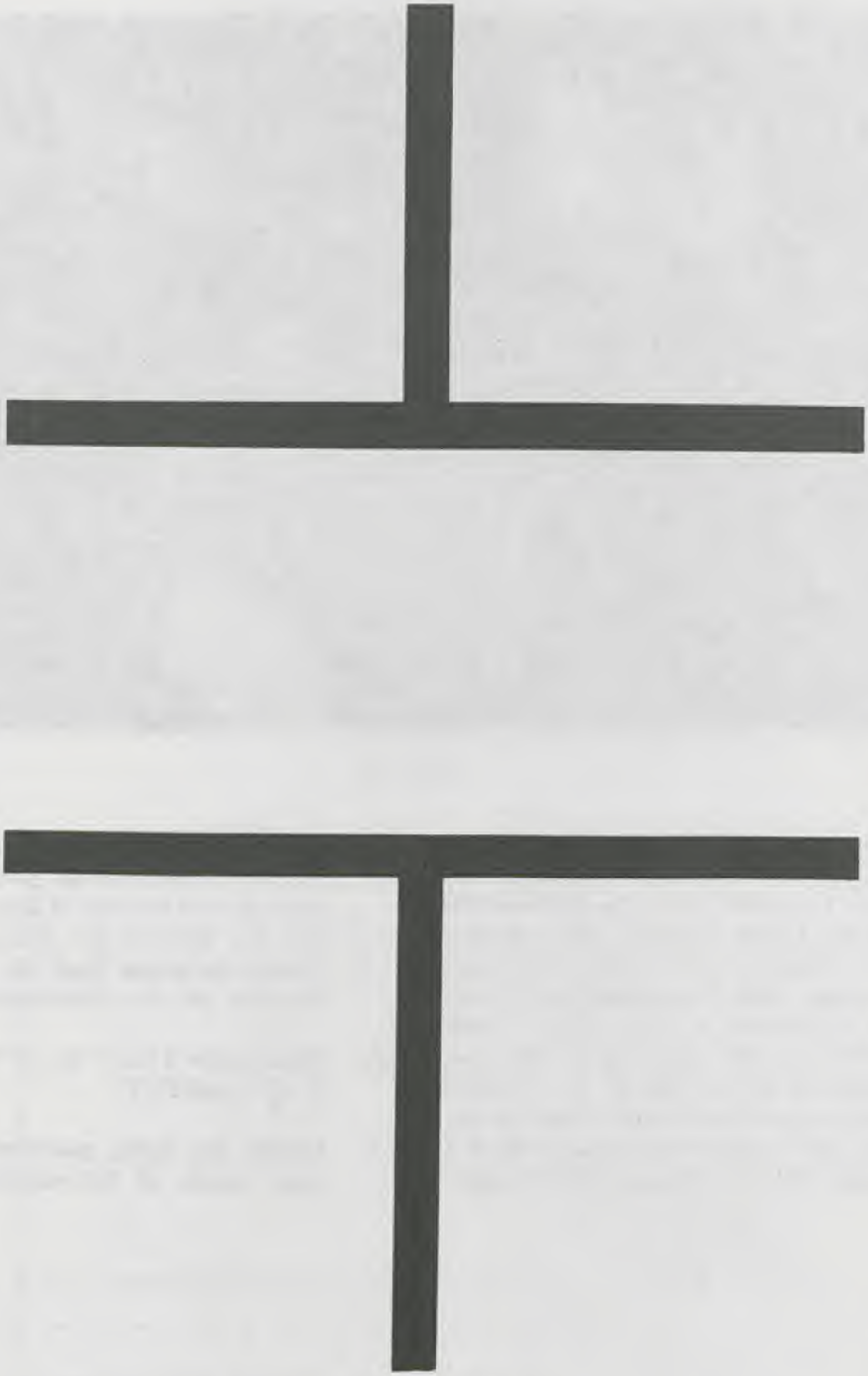


Figure 20. Parallel plates.

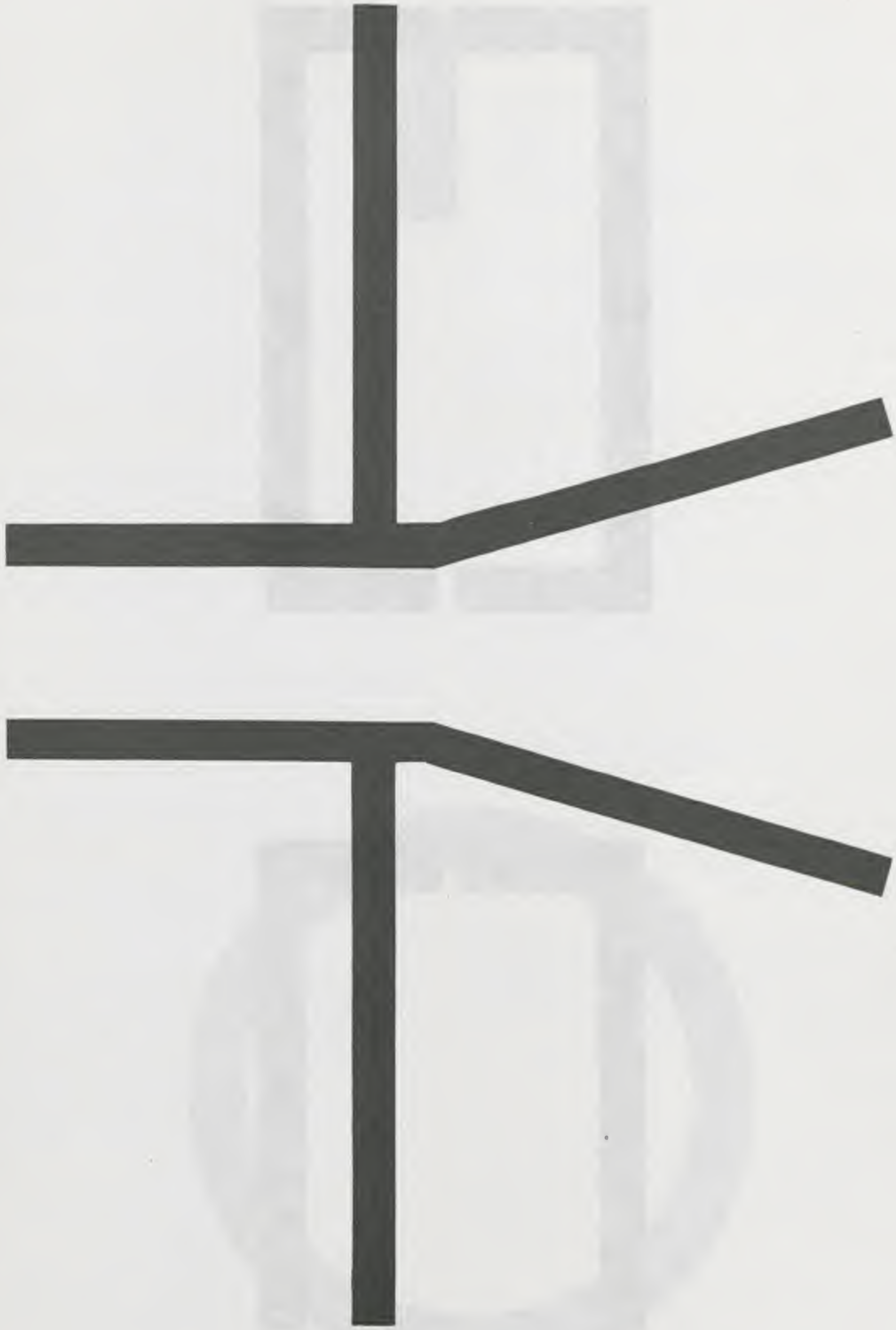


Figure 21. CRT deflecting plates.

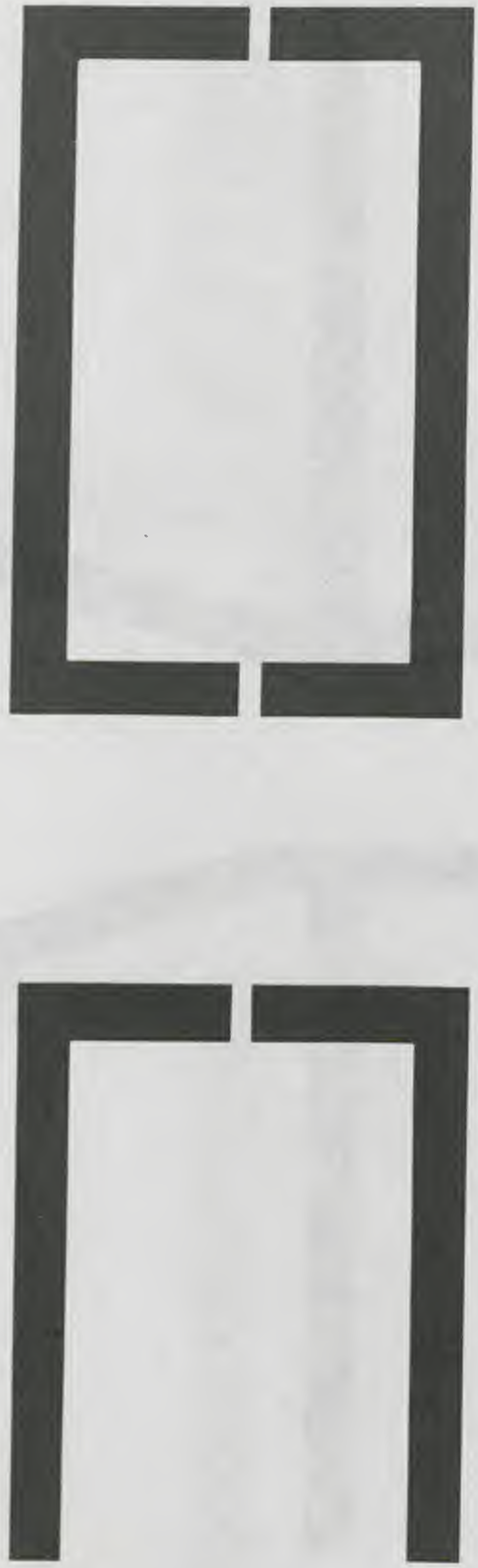


Figure 22. CRT accelerating electrodes.

Figure 23. Closed metallic conductor.

TREATMENT OF DATA

1. Draw the equipotential lines for each sheet of field-mapping paper. (Of course, these lines are just the cross sections of the equipotential *surfaces* which exist in the three-dimensional space.)

2. Draw field lines perpendicular to the equipotential lines.

Questions

1. What is an equipotential line (or surface)?

2. Why is it impossible for two different equipotential lines to cross?

3. What is a field line?

4. Why can two different field lines never cross?

5. What is the geometrical relationship of the field lines to the equipotential lines?

6. Are the field lines for two parallel plates parallel everywhere? How about near the ends of the plates?

7. What is the electric intensity inside a closed, charged conductor? A practical application of this result is electric shielding.

Calculations

The work done by an electric field on a positive charge q when it moves from a place where the potential is V_2 to a place of lower potential V_1 is

$$W = q(V_2 - V_1) \tag{5}$$

This is the definition or meaning of the term potential difference. The particle has gone from a position where its potential energy was qV_2 to a position where it is qV_1. The decrease in potential energy is $q(V_2 - V_1)$. If the particle is allowed to move freely in the field, this decrease in its potential energy will just equal the increase of its kinetic energy caused by the electric force.

Select a straight field line on your field map of two parallel plate conductors. A charged particle released on a straight field line will travel along the line. Why? When it travels between one equipotential line and another along a line of force, the work done on this particle is

$$W = F_{av}d \tag{6}$$

where F_{av} is the average force and d is the distance between two equipotential lines. Equations (5) and (6) are two different ways to calculate the same work. This means that

$$F_{av}d = q(V_2 - V_1) \tag{7}$$

Divide by d and q

$$F_{av}/q = (V_2 - V_1)/d \tag{8}$$

We recall that force divided by charge is electric intensity, so

$$F_{av}/q = E_{av} = (V_2 - V_1)/d \tag{9}$$

Start at the positive plate. Calculate E_{av} between that plate and the closest equipotential line to it on your field plot. Then calculate E_{av} between that first equipotential line and the next one. Continue until you come to the negative plate. Record your results in Table I.

Table I.

V_2	V_1	d	$E_{av} = (V_2 - V_1)/d$	$E = \Delta V/D$

In the formula for E in the last column of Table I, ΔV is the voltage across the plates and D is the distance between the plates. The Greek letter delta (Δ) is used as a shorthand to represent the difference between two values of a quantity. For example, $\Delta V = V_2 - V_1$. This formula is often used for calculating E between two charged parallel plates.

Questions

1. Did E_{av} remain constant or did it vary along the field line for which you did the calculations?

2. Are your measurements of E_{av} in good agreement with the value of E calculated from the formula, $E = \Delta V/D$?

KINETIC AND POTENTIAL ENERGY

Example. One of the fields that you mapped was that produced by accelerating electrodes like those in the cathode ray tube. In the CRT which you use for this module, the accelerating voltage is about 400 to 500 V. Calculate the velocity of an electron after it is accelerated through 400 V, assuming it starts with zero velocity.

The decrease in potential energy is $e\Delta V$, where e is the electron's charge and ΔV is the potential drop (here $\Delta V = 400$ V). This decrease of potential energy is converted to kinetic energy ($\frac{1}{2}\,mv^2$, where m is the electron's mass and v is its velocity).

The kinetic energy gained by an electron in passing through a potential difference of 1 V is equal to its loss of potential energy which is

$$e\Delta V = (1.6 \times 10^{-19}\ \mathrm{C})(1\ \mathrm{V})$$

$$e\Delta V = 640 \times 10^{-19}\ \mathrm{J}$$

This amount of energy is a common unit of energy in nuclear physics, and it is called the *electron volt.* A joule is the SI unit of energy (or work), and its abbreviation is J.

Using 400 V

$$e\Delta V = 640 \times 10^{-19}\ \mathrm{J}$$

Then:

$$\tfrac{1}{2}\,mv^2 = 640 \times 10^{-19}\ \mathrm{J}$$

Solving for v gives:

$$v = \sqrt{(2 \times 640 \times 10^{-19}\ \mathrm{J})/(9 \times 10^{-31}\ \mathrm{kg})}$$

$$= 1.2 \times 10^{7}\ \mathrm{m/s}$$

Questions

1. How much kinetic energy, in electron volts (eV), is gained by a proton that is accelerated through a potential difference of 1 V? Answer the same question for an alpha particle. (An alpha particle has a charge equal to two proton charges. A proton has the same size charge as an electron, but it is positive.)

2. What is the velocity of:
   a. an electron which has a kinetic energy of 1 eV?
   b. a proton which has the same energy?

3. A positively charged particle is released at some point on the 10-V equipotential line. Will it move toward the 8-V or toward the 12-V equipotential line? What is the answer for an electron?

4. An electron enters the electric field midway between two deflecting plates. The electron has a velocity of 8×10^{6} m/s perpendicular to the field lines, as shown. What kinetic energy does it have when it hits the positively charged deflecting plate? Express this in joules and in electron volts. The mass of the electron is 9×10^{-31} kg; its charge is -1.6×10^{-19} C. [Hint: Remember that the increase in kinetic energy ($\frac{1}{2}\,mv^2$) is equal to the decrease in electrical potential energy ($e\Delta V$).] (See diagram, page 24.)

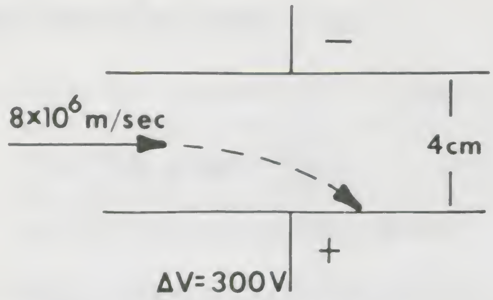


Diagram for Question 4.

5. Color TV sets use a voltage of about 24,000 V to accelerate the electrons in the electron gun. Black and white sets use only about 12,000 V to do this.

   a. How does the kinetic energy of an electron leaving the electron gun in a color set compare to that of one in a black and white set?
   b. How do the velocities compare?

6. In a TV tube, the electron gun is about 10 cm long. Calculate the average force that the gun exerts on the electrons for a color set and for a black and white set. (These answers may not seem very large, but remember that the electron's mass is 9×10^{-31} kg).

ELECTROSTATIC DEFLECTION IN THE CRT

Getting inside a cathode ray tube and watching the electrons move about would help one to learn how a cathode ray tube works. That, of course, is not possible. Motion pictures or strobe pictures of an electron as it moves along would be nice, but electrons are too small to photograph. Although it is possible to take pictures of their paths in cloud chambers and bubble chambers, student laboratories do not have the equipment to photograph electron paths. Instead, we show here the results of experiments and theory in Figures 24A and 24B, which are drawn to scale. Figure 24A is a drawing of electron paths in a CRT from the point where they enter the space between the deflecting plates to the screen. Figure 24B is an eight-times magnification of the space between the deflecting plates. The top set of dots, which go straight across the page, mark the path of an electron with no deflection. The curved set of dots show a deflected path.

Treat Figure 24 as though it were data taken by a scientist or engineer you are helping with an experiment and as if it were the actual size of the path of the electrons in the CRT. The objectives of the scientist are:

1. To compare the undeflected and deflected motions of an electron in a CRT
2. To see how closely the paths can be calculated using Newton's laws when the forces acting on the electron are known
3. To calculate how much the beam is deflected by gravity

Questions and Problems

The scientist tells you that the time it takes an electron to go from the place marked by one dot to the next is 4×10^{-10} s. He asks you to make whatever measurements (on Figure 24) and calculations you need to answer the following questions for the undeflected beam:

1. a. What is the speed of the electron in meters/second (m/s) and in miles/hour? (1 m/s = 2.24 mi/h)
   b. What voltage is required to accelerate an electron to this speed if it starts from rest? The scientist asks this question because he wants to know if the CRT is working well and accelerating electrons to the speed expected from the voltages he is using.

2. What is the length of the plates? This is marked L_p in Figure 24A. If you were working in a laboratory, you would make this measurement on the tube. For this exercise you can make it on Figure 24A, which is drawn to exact size.

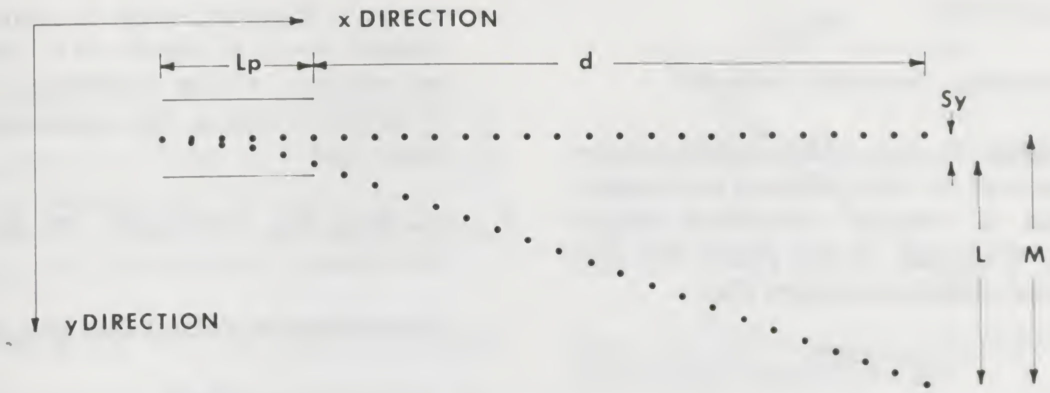


Figure 24A. Electron paths, drawn to scale, in a CRT.

3. What is the spacing of the plates? This is the distance D in Figure 24A.

4. What is the distance from plates to screen? This is the distance d in Figure 24A.

5. How long a time is the electron between the plates?

6. How much time does it take the electron to travel from the plates to the screen? There are two ways to do this. Try both ways.

The scientist tells you that the curve path in Figure 24 was obtained by putting 100 V across the deflecting plates. He asks you to see how well calculations of the deflected path, based on Newton's Laws of motion, agree with the experimental path in Figure 24. The next several paragraphs will help you do this.

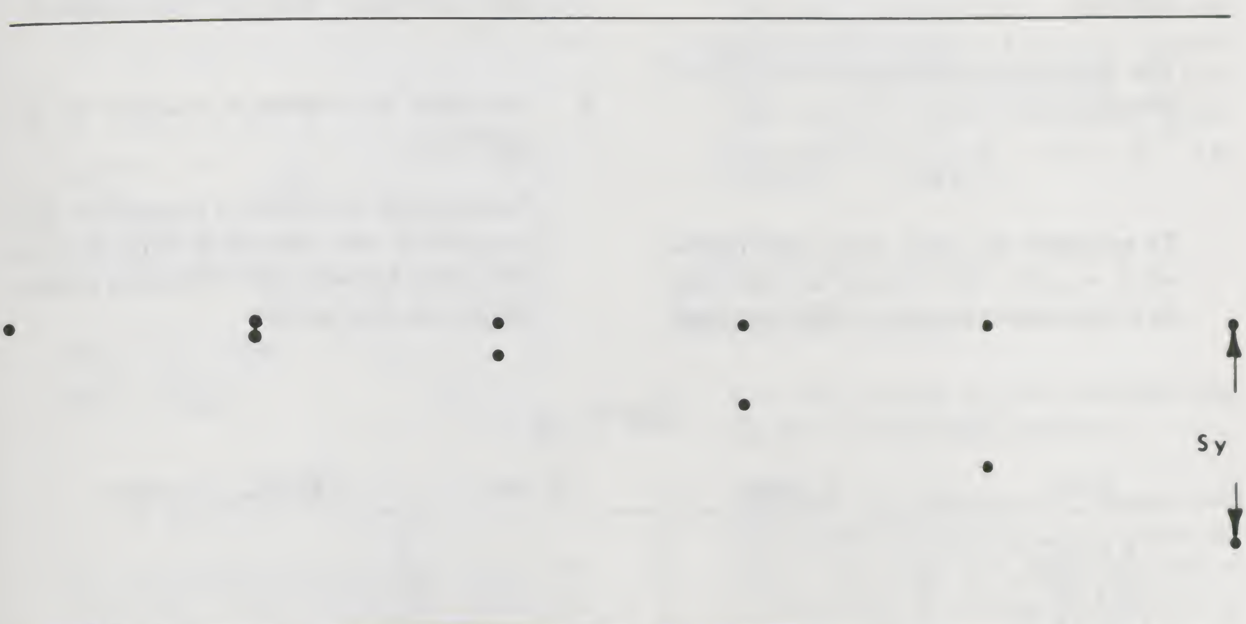


Figure 24B. An eight-times magnification of the region between the deflecting plates.

CALCULATIONS

1. Calculate E, the electric intensity.

   We know from the field-mapping experiment that the field between two parallel plates is constant everywhere except near the edges of the plates. We also learned in that experiment that

   $$E = \Delta V / D$$

   where E is the electric intensity, ΔV is the deflection voltage (100 V), and D is the distance between the plates. You have previously measured D, so E can be calculated.

   You should notice that for SI units, ΔV is in volts and D in meters. Thus, from $E = V/D$, E is in volts/meters (V/m). When we defined field intensity by the equation $E = F/q$, force divided by charge, we said the units are newtons/coulomb (N/C). Both V/m and N/C are correct units for E, and they are completely equivalent.

2. Calculate the deflection force on the electron.

   The force on a charge q in a field of intensity E is

   $$F = qE$$

   To calculate the force on an electron we set $q = 1.6 \times 10^{-19}$ C and use the value of E calculated in step 1. This force acts in the y-direction which is shown as straight down in Figure 24A. This is perpendicular to the undeflected beam direction, which is the x-direction in Figure 24A.

3. Calculate the acceleration in the y-direction.

   The acceleration in the y-direction is

   $$a_y = F_y / m$$

   Subscripts y are used on a and F to help us remember that the acceleration and force we calculate here are in the y-direction shown in Figure 24A.

4. Calculate velocity in y-direction.

   The velocity in the y-direction at time t is

   $$v_y = a_y t_y$$

   This formula can be used to calculate velocities in the y-direction for the times $t = 4 \times 10^{-10}$s, 8×10^{-10}s, 12×20^{-10}s, 16×10^{-10}s, and 20×10^{-10}s. Enter your calculated values of v into Table II.

5. Calculate the distance traveled in y-direction.

   To calculate the distance traveled by the electron in the y-direction while it is in the space between the deflecting plates, we can use the formula

Table II.

t (s)	v_y (m/s)	S_y (m)	$S_{y\ \mathrm{measured}}$ (m)
4×10^{-10}			
8×10^{-10}			
12×10^{-10}			
16×10^{-10}			
20×10^{-10}			

$$S_y = 1/2\, a_y t_y$$

Calculate S_y for the times in Table II and enter the results. The values of S_y measured in Table II are to be obtained by measuring the distances between the curved (deflected) path and the straight (undeflected) path in Figure 24.

6. Calculating the total beam deflection.

The particle travels in a straight line after leaving the electric field because there is then no force acting on it. In Figure 24 the electric field acts only between the plates. (In practice, as you found in the field-mapping experiment, the field does not stop at the edges of the plates but continues more weakly for some distance beyond them.)

When the electron is in the space between the deflecting plates and the screen, it travels with a velocity component in the x-direction given by v_x, which you determined at the beginning of this exercise. The y-component of the velocity is the value of v_y at time $t = 2 \times 10^{-9}$ s. The sum (resultant) of vectors v_x and v_y gives the velocity, v, of the electron in this region, as shown in Figure 25.

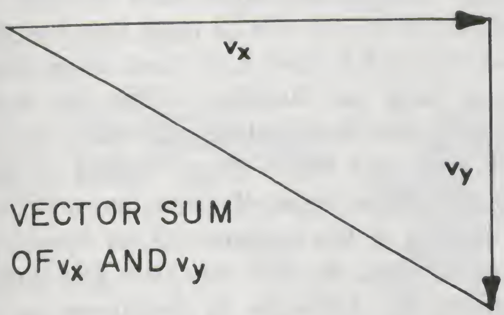


Figure 25.

By multiplying each of these vectors by the time T that it takes the electron to travel the distance from plates to screen (d in Figure 24), we get the diagram of Figure 26.

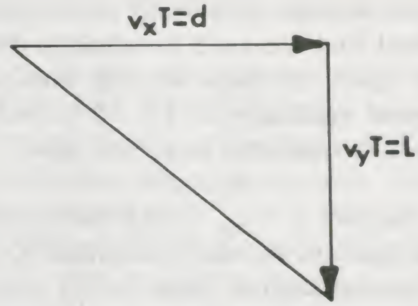


Figure 26. Vector diagram for the displacement of the electrons in the field-free region.

From $L = v_y T$ and $d = v_x T$, dividing L by d

$$L/d = (v_y T)/(v_x T) = v_y/v_x$$

or

$$L/d = v_y/v_x$$

$$L = (v_y d)/v_x$$

All the numbers on the right of this equation are known and so L can be calculated. This is the additional amount by which the electron moves in the y-direction while going from plates to screen (the distance d in Figure 24). The total distance that the spot will move on the screen is L plus the distance moved in the y-direction while the electron was in the space between the plates. This distance is S_y at $t = 20 \times 10^{-10}$ s in Table II.

Questions and Problems

1. How well do the S_y you calculated and the S_y you measured compare?

2. Calculate the distance the electron will fall because of gravity as it moves between the plates and judge whether or not the effect of gravity is significant in this case. Assume the plates are uncharged. (Gravitational acceleration is $g = 9.8\ \text{m/s}^2$.)

3. An electron starts from rest in the same field that was used to calculate distances in Table II. How far will this electron move vertically in 2×10^{-9} s and what will its y-velocity be at that time?

4. Calculate $L + S_y$. This is the total beam deflection, M, on the screen. Compare your calculated value of M with that shown in Figure 24.

5. Calculate the *sensitivity* of the CRT. This is obtained by dividing the distance M the beam is deflected by the voltage required to produce the deflection.

6. An electron beam enters the electric field between two deflecting plates at a point midway between the plates and in a direction perpendicular to the field lines. After the electrons emerge from the plates, they move in a straight line. Prove that if this straight line is extended back into the region between the plates, it passes through the midpoint of the region.

EXPERIMENT 3. Electrostatic Deflection of the CRT Beam

In this experiment you will do the following:

1. Produce a graph of the displacement of the CRT beam spot vs. deflection voltage, for both sets of deflection plates.

2. Compare observed and calculated values of deflection.

3. Compare the vertical and horizontal deflections for equal applied voltages and explain any difference.

4. Observe and explain the effects of varying the acceleration voltage.

5. Produce a horizontal sweep manually.

UNDERSTANDING THE CIRCUIT (OPTIONAL)

The internal electrical circuit of and the controls for the CRT for this module are shown in Figure 27. A single 500-V power supply is used, and resistors, used as voltage dividers, provide the lower voltages needed for the grids, the first anode, and deflection plates.

You may want to know how the CRT works. Here's a brief explanation.

Let's begin at the filament of the CRT, where the electrons that are going to form the beam start out. The power supply provides a current through the filament, which heats the cathode so that electrons will be "boiled off." For this particular tube, a filament voltage of 6.3 V supplies the right current. The cathode and the filament are connected together so they are at the same potential.

The first grid is kept a few volts more negative than the cathode so that it will repel slowly moving electrons back toward the cathode. It is not able to repel faster moving electrons, but it does slow them down a little bit as they go through it into the region between the first and second grids. So the first grid acts like a gate. Making it more negative allows fewer electrons to go through it; making it less negative allows more electrons to pass. In this way, the grid voltage controls the *intensity* or brightness of the beam. The beam must not be intense enough to overheat the phosphor coating on the face of the CRT and thus "burn" a hole in it when the beam is aimed at one spot too long. For this reason, it is important that the first grid always be kept a few volts negative with respect to the cathode. A positive first grid can damage the tube.

When the High Voltage Control is in the full counterclockwise position, the cathode (2) and the second anode (9) are at the same voltage; when it is fully clockwise, the second anode is 500 V above the cathode.

When the Focus Control is fully counterclockwise, the first anode (5) and the cathode (2) are at the same voltage, and the electrons will be stopped by the first anode. As the Focus Control is turned clockwise, the first anode becomes more positive than the cathode and the beam will be able to go through.

So that it is not possible to get shocked, the voltage at the High Voltage Meter terminal is only 1/100 of the high voltage and at the Deflection terminals it is only 1/10 of the deflection voltage.

When the Deflection Plate Selector switch is turned to "T," the deflection voltage is applied to the top deflection plate: likewise for Bottom, Left and Right.

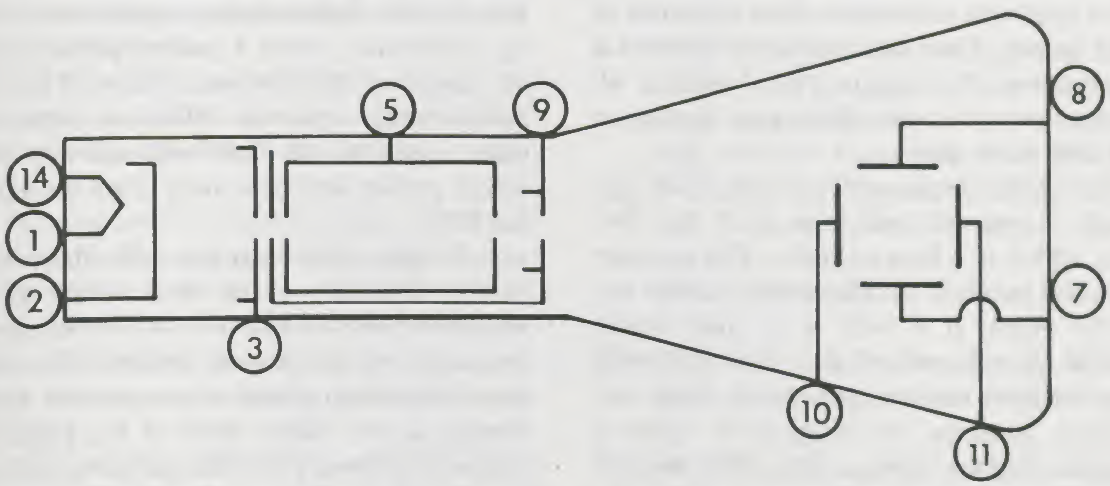
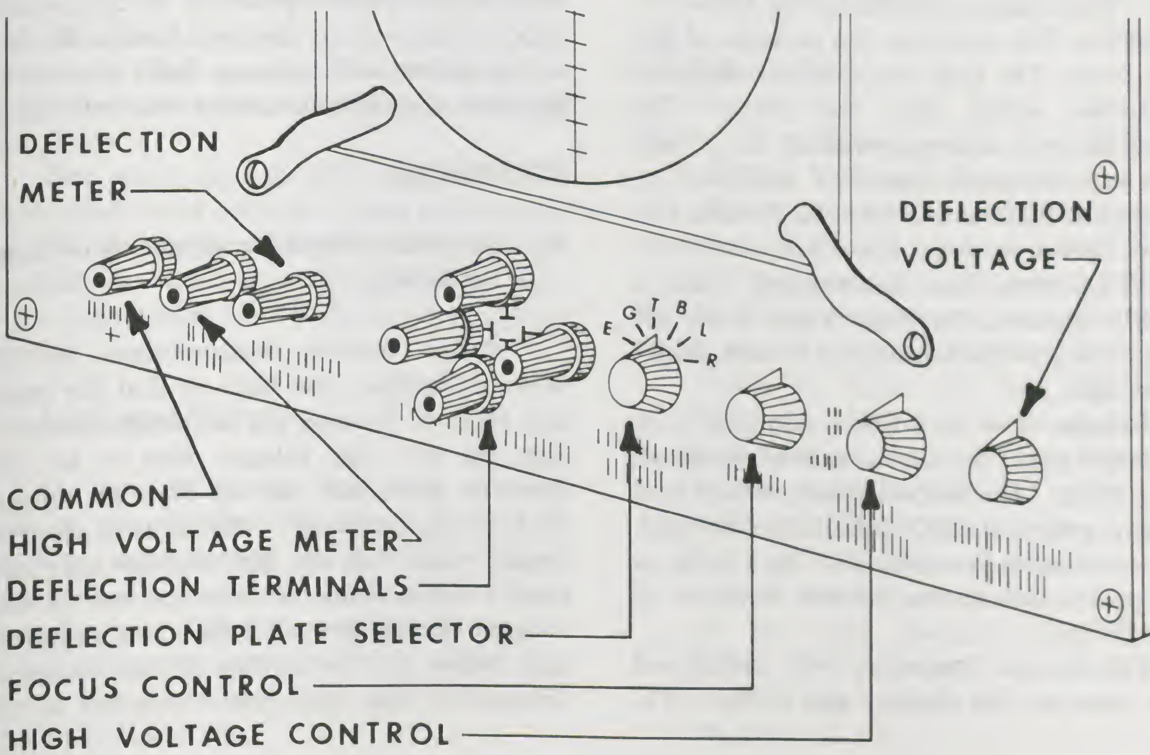


Figure 27. The internal circuit of the CRT (above) and the control panel (below).



The second grid is connected to the second anode by a wire inside the CRT. In operation, the second anode and also the second grid are kept at a high voltage relative to the cathode. The potential of the second anode can be varied from a value equal to that of the cathode, up to the operating potential of about 500 V above the cathode. Electrons leaving the cathode are attracted to the second grid by this high (500 V) positive potential. The first grid allows only the electrons which are moving relatively fast in the desired beam direction to pass. The second grid then accelerates these electrons to higher speeds. Since it is positively charged it also narrows the beam by absorbing all electrons except those which pass through a small hole in its center.

The high-speed electrons which do get through the second grid then enter the first anode, which is a long cylinder. The purpose of the first anode is to still further narrow the electron beam. It is held at a much lower potential than the second grid. This may seem strange at first, but the cylindrical shape and the lower potential are designed to create a particular electric field pattern. This electric field deflects all of the electrons which pass through it toward a single point, called the *focus.* Two factors determine the nature of the electric field and thus the position of this focus point. The first factor is the shape of the anode, which does not change. The second factor is the potential of the anode, which can be varied from 0 V to 180 V by turning the focus control knob. Turning this control moves the focus toward or away from the CRT screen. When the electron beam is properly focused, the focus point is on the screen, and the beam produces a small, bright spot of light.

Because it is at a lower potential than the second grid, the first anode slows down the electrons. The second anode, which is at the same potential (500 V) as the second grid, again accelerates the electrons. They have, as they strike the screen, kinetic energies of about 500 eV.

The four electrodes we have mentioned so far make up the electron gun of the CRT. The picture tube in your TV set has an electron gun very much like this one. Notice that all of the voltages in the electron gun are applied to a set of in-line electrodes which are lined up parallel to the beam. The only electrical forces the electrons have felt up to this point (except for the focusing forces of the electric lens) have been parallel to the axis of the tube.

Forces perpendicular to the axis are needed to deflect the beam. These are provided by two pairs of deflecting plates, a horizontal pair and a vertical pair. As you found in the field-mapping experiment, a voltage difference across a pair of plates creates an electric field between them. The field produced by a pair of deflection plates is at right angles to the beam and exerts a force which pushes electrons away from the axis of the CRT.

In this experiment you will connect one of the deflection plates to a voltage source which can be varied from 0 to 50 V below the potential of the second anode. The other three deflection plates are connected to the second anode. Since three of the plates are connected directly to the second anode and the fourth is connected to it through the voltage source, all of the deflection plates are kept at or near the potential of the second anode. This prevents electrons from collecting on the plates and setting up fields that might interfere with beam focusing and deflection.

PROCEDURE

A. Observations and Measurements of Beam Deflection

Before making measurements of the beam deflection, you have to find the beam and focus it. Turn on the AC power but don't turn up the high voltage. Wait to see the filament glow, then turn up the high voltage, find the electron beam, and focus it. Use the largest value for the high voltage that still gives a sharp focus. Measure and record this voltage. (Remember that the power supply is run below the potential of the *common* terminal so that the positive terminal of the

meter goes to the common terminal.) Do not change this voltage until your graph is finished. Now connect the negative side of the meter to the *deflection meter* terminals. Turn the *deflection plate select* knob to connect the top of the vertical plate ("T").

The movable plastic grids were designed to make the reading of the beam deflection easier. Place a grid over the tube face, centering it on the undeflected beam position. (You could also use crossed rulers.) Make sure that the deflection is parallel to the vertical axis. You can do this by measuring the deflection voltage and observing the line the beam moves along.

Set the deflection voltage to zero. The beam spot should be near the center of the tube, and the grid should be centered on the spot.

Prepare a sheet of graph paper. Label the x-axis "deflecting voltage," with a scale from zero to 50 V. Label the y-axis "deflection," with a scale from zero to about 4 cm. Assume that the deflection is zero when the deflection voltage is zero, and plot the point (0,0) on your graph.

Increase the deflection voltage in 5-V steps, recording the beam deflection for each voltage. Plot all of the values on the graph. Continue until you reach the maximum deflection voltage, or until the spot leaves the tube face. Then repeat the measurements using a deflection plate which gives horizontal deflections.

Plot your data on the same piece of graph paper using different marks so that you can tell the graphs apart. Repeat the entire experiment using the *smallest* possible value of the high voltage for which the beam can be focused.

B. Horizontal Sweep

In an oscilloscope, the beam can be made to move horizontally across the face of the tube at a constant speed. This is called *horizontal sweep.* Try to produce this effect manually by rotating the deflection voltage control. Start the sweep at the far left of the screen, then turn the knob as rapidly and uniformly as you can.

C. Simultaneous Horizontal and Vertical Deflection

With two batteries, you can observe what happens if you put voltages on both sets of plates at the same time. Connect two batteries as shown in Figure 28. Notice the effect on the beam as each battery is connected. How will the beam deflection be affected if the polarity of each battery is reversed? Explain.

TREATMENT OF DATA

1. Draw a smooth line through each set of points on the graph paper having the same values of high voltage (V_h). This will produce four lines, since you used two values of V_h for both the vertical and the horizontal deflections.

2. What is the shape of the lines obtained?

3. What effect does changing the accelerating voltage (V_h) have on the lines?

4. For the same values of V_h, and applied deflection voltage, are the horizontal and vertical deflections equal? If they are not equal, which deflections are larger?

CALCULATIONS

1. In a previous exercise, you helped a scientist calculate the deflection of a CRT beam. Use that method to calculate the vertical deflection of a CRT beam. Use that method to calculate the vertical deflection for deflection voltages of +10 V and +15 V for the highest accelerating voltage for which you took data in the laboratory. The dimensions of the CRT deflection system are given in Figure 28. If you used a different tube, your instructor will give you the proper values for your CRT. The dimensions of the vertical and horizontal deflection plates are the same. Because the plates are flared, their effective separation is an average value which lies between 0.42 cm and 1.0 cm. It turns out to be 0.56

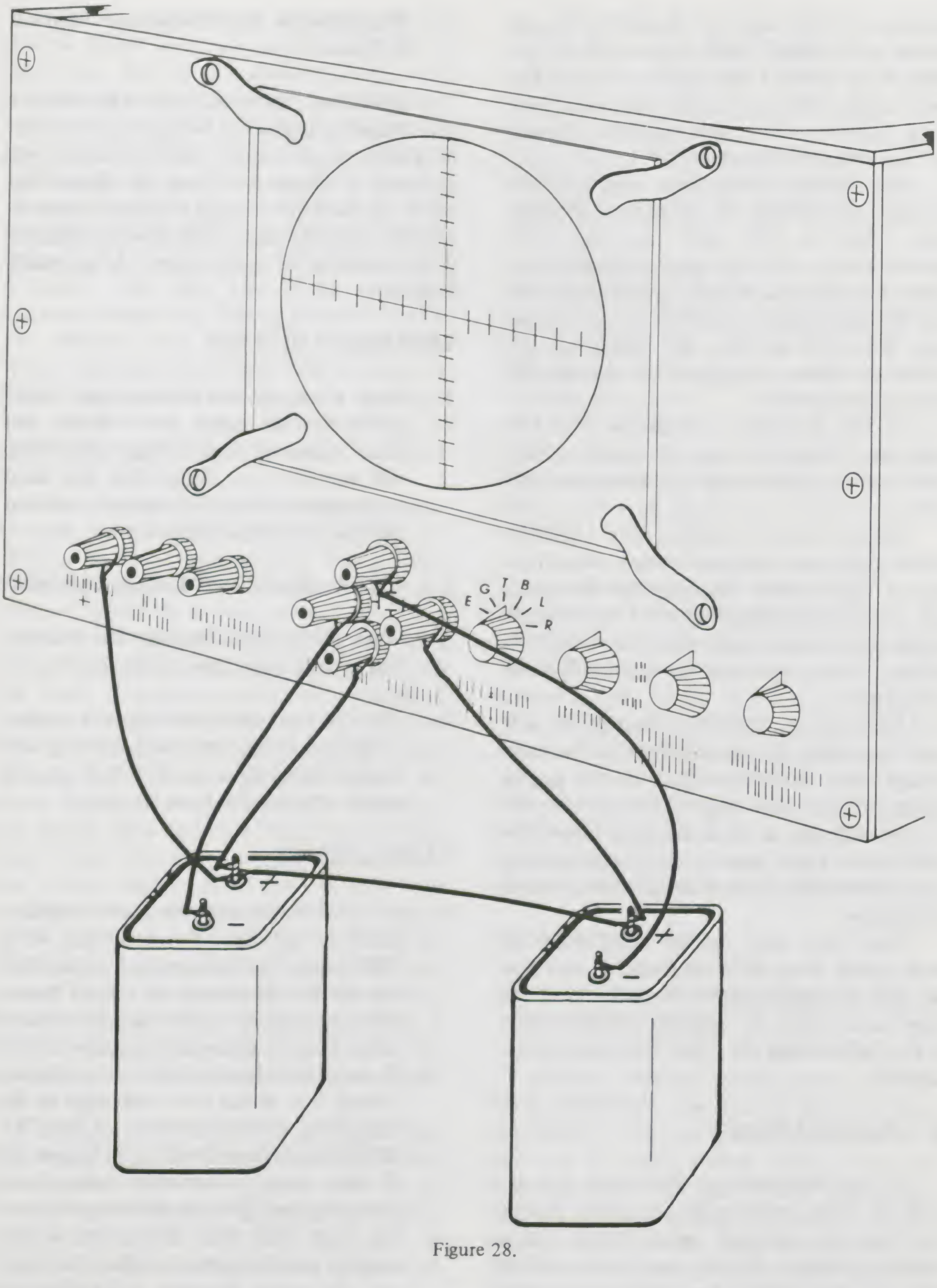


Figure 28.

cm. Therefore, in your calculations assume the plates to be flat (not flared) spaced 0.56 cm apart. The horizontal deflection plates are closer to the screen than the vertical plates.

2. Perform the deflection calculations for the horizontal deflection plates using the same accelerating and deflecting voltages. You may save yourself time by noticing that only the distance from deflection plates to screen is different in the horizontal deflection as compared to the vertical deflection. Up to the point in the calculations where you use this number, everything will be the same and need not be recalculated.

3. Calculate the *deflection sensitivity* (deflection divided by the voltage) of each set of plates.

QUESTIONS

1. Does the deflection increase, decrease, or remain the same when the accelerating voltage (V_h) is decreased and nothing else is changed? Explain why this should be so. (Hint: Ask yourself the following questions. How does increasing voltage affect v_x? How does the change in v_x affect a_y and how does it affect the time the particle is between the deflecting plates? How do these, in turn, affect the deflection S_y and the velocity v_y at the point where the particle just leaves the region between the plates? How do these and the change in time to go from deflection plates to screen change the deflection that occurs between plates and screen?)

2. How do your calculations of the deflection compare with the values? What assumption made in the calculations might cause differences between calculated and measured deflections?

3. When you plot the deflection of the electron beam as a function of the deflecting voltage, the points lie on a straight line. When you change the accelerating voltage, the slope of the straight line changes. If you doubled the accelerating voltage, would you expect the slope to:

   a. double
   b. stay the same
   c. reduce by a factor of the square root of 2
   d. reduce by a factor of 2
   e. reduce by a factor of 4

4. A CRT is operated with the second grid at +500 V, the first anode at +100 V, and the second anode at +500 V, all with respect to the cathode. Assuming that the electrons are emitted from the cathode with no (or very little) kinetic energy, calculate the kinetic energy and the velocity of an electron:

   a. as it passes grid #2
   b. while it is inside anode #1
   c. as it passes anode #2
   d. Describe the electron's motion in words.
   e. How does the electron's speed change while it is in anode #1? Why?

07-001721-2